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Improving dynamic proximity sensing and processing for smart work-zone safety

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ABSTRACT

Equipment/vehicles striking workers is one of the most frequent accidents that occur in roadway workzones. As a means of prevention, a number of active technologies have been developed to provide proximity sensing and alerts for workers and equipment operators. However, most of these systems are based on the distance/proximity level between workers and equipment and neglect the variations caused by different settings and environmental conditions, such as equipment types and approaching speeds, which can result in inconsistency and delay of the systems. As of yet, previous research has insufficiently investigated these issues. This research addresses the issues by utilizing the Bluetooth Low Energy (BLE)-based proximity sensing and alert system developed by the authors. This paper discusses the development and assessment of parameter adjustment and adaptive signal processing (ASP) methods. The research conducted field trials in various dynamic conditions and settings to assess the performance of the system. The test results showed that the parameter adjustment function reduced the inconsistency of the alert distances resulting from different types of equipment, and that the ASP method reduced the time delay resulting from high approaching speeds. The developed proximity safety alerts system provides stakeholders with better understanding of dynamic spatial relationships among equipment, operator, workers, and a surrounding work environment; thus, improving construction work zone safety.

1. Introduction

In construction, safety is as important as successful completion of a project. Worker safety should be addressed and managed successfully during the entire construction period. Although the issue of safety has garnered urgent attention in construction [1,2], and considerable efforts have been made, the number of fatal occupational injuries at road construction sites has remained relatively constant over the last decades. According to the U.S. Bureau of Labor [3], one of the most common causes of loss of life at construction sites are accidents resulting from collisions between workers and a vehicle or equipment. This type of accident accounts for nearly half (443 deaths) of 962 deaths recorded in road construction sites from 2003 to 2010 [3,4].

Signage, traffic control systems, flaggers and other worker safety measures are used to maintain and promote safety at road construction sites. However, these passive safety devices and measures are incapable of alerting construction operators and workers in real time during a hazardous proximity situation [5]. Consequently, a variety of active technologies have been developed and applied to provide construction proximity sensing and alerts to workers and operators. Ruff [6,7] explored many technologies (e.g., radar, sonar, and infrared, UWB, GPS, and vision) for the application in the mining industry; some of these are the same technologies that are currently used in proximity sensing in passenger cars. These technologies suffer from unique limitations including light sensitivity, line of sight, form factor, cost, weight, limited field of view, and feasibility in the harsh construction environment. In addition, they generate mainly one-directional alerts for the operator not for pedestrian workers. Although these approaches provide proximity warning in certain conditions, most of them merely rely on the distance/proximity level between equipment and workers, which leads to frequent nuisance alarms [8,9]. Furthermore, most of the systems are developed and/or tested on selected equipment or at certain approaching speeds without considering inconsistency and unreliability caused by changes in these settings.

This problem indicates a need for investigating a solution that mitigates the inaccuracy of proximity sensing and alert systems caused by various types of equipment and different approaching speeds. To explore a solution to these problems, this research uses the Bluetooth Low Energy (BLE) technology-based proximity sensing and alert system that was first demonstrated as a prototype by Park et al. [10]. This BLE

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system is software-programmable that allows modification of the system. In this research, we modified the BLE proximity sensing and alert system by developing and embedding two features to it (i.e., a parameter adjustment function and a signal processing method). The purpose of these developments is to improve the consistency and reliability of the BLE proximity sensing and alert system for different types of equipment at different speeds. In the following section, an extensive review of proximity related research, in this aspect, is discussed. Then, methodologies, experimental studies, analysis, and discussion follow.

2. Literature review

2.1. Proximity sensing and alert systems

Over the last decade, researchers have attempted to use various sensing technologies, such as radar, video camera, radio frequency identification (RFID), magnetic field detection, BLE and others to provide a real-time monitoring systems [6,11–18]. Marks and Teizer [5] provided a method for evaluating proximity sensing and alert technology for safe construction equipment operation. Park et al. [10] evaluated commercially available proximity sensing and alert systems (i.e., BLE, magnetic field detection and RFID systems) through field trials, and Park et al. [19] developed a directional aware proximity system. Chae and Yoshida [17] used three tags (equipment, person, and location) to add additional location information for effectively detecting and preventing potential colliding incidents; although this method is advanced, the use of location tags in dynamic construction workzones may present challenges as previous research identified that location sensing technologies have problematic issues in many conditions (e.g., absence of line of sight, signal interference and reflection) [20–22]. Luo et al. [23] discussed the impact of workers' responses to proximity warning by conducting a series of tests at a construction site. Ruff [7] discussed the capabilities and challenges of available sensing technologies (e.g., radar, video camera, and RFID systems) for monitoring blind spots around haul trucks. Similar tests were conducted, and a guidance for evaluating and implementing proximity systems for mining equipment was developed by Ruff [6].

Although several systems have been found to be capable of providing reliable proximity alerts under certain circumstances, many systems showed inconsistency and thus unreliability in detection range, especially when environmental settings in which the systems are deployed change. Park et al. [11] conducted the coverage experience of different types of construction equipment by using three proximity sensing and alert systems, which are BLE, RFID, and magnetic field-based proximity sensing and alert systems. Their results showed that the alert range abruptly changed, although the same settings were used, when the tested equipment was changed from a truck to a wheel loader. A similar phenomenon is also found in a study conducted by Marks and Teizer [12]. In addition to these findings, Ruff [6] stated, “required detection characteristics for a system depend on the equipment it will be installed on”, which suggests the same problem. Besides the type of equipment, other parameters, such as ambient temperature and relative humidity, are also found to impact the results of proximity sensing and alert systems [5]. Similar issues of sensing technologies are also reported in a recent study [24]. These statements suggest that sensing systems can perform inconsistently even when they are applied in the same/similar manner. Such an issue has not been sufficiently studied or addressed by state-of-the-art research in the proximity sensing domain.

Previous research suggests another significant challenge other than the impacts caused by different test conditions; delays of alerts for proximity sensing and alert systems under high approaching speeds have also been found in several studies. The National Institute for Occupational Safety and Health [25] tested an electromagnet-based proximity system for mining in various testing scenarios. The test results showed clear evidence of this delay. Their tests with multiple pieces of equipment and various moving speeds revealed that the detection distance dropped in all cases. For example, one of their many tests showed that the distance dropped from 43 in. (1.09 m) to 25 in. (0.64 m) when the speed increased from 3 in./s (0.27 kilometers per hour (kph)) to 32 in./s (2.92 kph). A recent experimental study emphasizes the same finding related to the distance drop when the proximity sensing systems are subjected to various approaching speeds [11]. Ruff [6] pointed out that the parameters, such as operator and pedestrian reaction times, maximum speed of the equipment, braking distances and the equipment dimensions, must be considered when determining a detection range at high approaching speeds. In addition, researchers [18,26–28] conducted state and space modelling using 3D position, orientation and velocity to more effectively model the alert range.

Despite the previous research efforts, the literature clearly presents a strong need for exploring the problems in regard to inconsistency and delay of proximity warning systems. To overcome the discussed limitations with which currently available proximity sensing and alert systems still struggle, this study developed a parameter adjustment function and a signal processing method, which were validated through field trials.

2.2. Bluetooth Low Energy (BLE) technology

This section provides a brief overview of the technology, BLE, used in this research. BLE was developed and adopted in 2010, and compared to conventional Bluetooth technology, BLE offers many benefits, such as low cost, low energy usage, and minimal infrastructure requirements [29] while maintaining other beneficial characteristics of the conventional Bluetooth technology. Because of these benefits, BLE technology has recently gained in popularity with many industries. One study by Martin et al. [30] conducted tracking research. Although tested in a small, limited setting, they acquired an accurate tracking of 0.53 m accuracy. In addition, several BLE-based systems have been developed for construction safety [13,16] and tracking [31], which proved the technical feasibility of BLE technology in construction applications.

Although the potentials for BLE technology have been well recognized and actively explored in other research domains during the last decade, only limited numbers of research studies have been conducted in the construction domain. The first BLE-based proximity sensing and alert system was prototyped by the Robotic and Intelligence Construction Automation Lab at the Georgia Institute of Technology, and first introduced by Park et al. [10]. This research used the same platform to develop and test the parameter adjustment function and signal processing method to address the discussed challenges discovered in the previous literature review.

3. Objectives and scope

The primary objective of this study was to address the problems of inconsistent performance and potential delay of a proximity alert system by developing two methods in the BLE-based proximity sensing and alert system. This advancement will be a step forward for the system with an ultimate goal for improving worker's safety through the system. The additions of the methods were to increase both the consistency and accuracy of the system in various settings (e.g., various pieces of equipment and settings of the sensing system) and dynamic situations (e.g., various speeds), which presented challenges to previous developed and/or tested systems. The methods should overcome practical limitations, such as the inconsistency of results under different equipment settings, and the distance drop at high approaching speeds which are currently present in state-of-the-art proximity sensing and alert systems. To validate the developed methods, this study conducted various field trials to simulate hazardous situations with workers and equipment and analyzes the data to assess the performance of the proposed methods.